

*Facility*

THE PENNSYLVANIA STATE UNIVERSITY  
DEPARTMENT OF GEOCHEMISTRY AND MINERALOGY  
UNIVERSITY PARK, PENNSYLVANIA

**UNPUBLISHED PRELIMINARY DATA**

Study of Structural and Mineralogical Significance of  
Meteorite Impact Sites, including Mineral Paragenesis,  
High Pressure Polymorphs, Microfractures and Quartz  
Lamellae.

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**PLEASE NOTE:**

**The following maps are not included in this report:**

**Maps 1 and 2 of the Lac Couture Crater and surrounding area;  
Map of the K&fels Crater, Austria.**

**These will be forwarded as soon as they are cleared through  
the drafting office, and are printed.**

**D.P. Gold.**

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## INTRODUCTION

Orientated specimens have been collected from the following craters: Brent, Ontario; New Quebec, Northern Quebec; Lac Couture, Northern Quebec; and Kofels, Austria. Maps, showing the sample locations, are available in this report (New Quebec, Lac Couture, Kofels) and in the previous report (Brent). Some unorientated samples are available from the Ries Kessel area, Germany, and from the Holleford crater in Ontario. The collection covers craters from one mile in diameter (Holleford) to seven miles in diameter (Lac Couture). The sampling of a large crater such as Manicougan (Quebec) or Vredefort (South Africa) is desirable to round out the study.

The New Quebec crater (approximately two miles in diameter) is the best studied and best sampled of these craters. Structural analysis of sheeting joints, joint planes, primary foliation, secondary foliation (shear planes), and lineations in both the rim and country rocks, indicate that the crater is a superimposed feature and that very little erosion has taken place since its formation. Shear zones in the rim rocks most probably are pre-crater in origin.

The rocks seen during the detailed mapping in the cardinal directions around Lac Couture, and on selected islands within the lake, showed no unusual deformation features. Polymict breccia erratics occur uniquely in a fan shaped area westward of the crater, which is the prevailing direction of glaciation. Unusual deformation cleavages and lamellae were observed in quartz from

granite gneiss inclusions in the breccia. Glassy shards and pebbles were picked up on a beach two miles west of the crater. The polymict breccias have not yielded any coesite; as yet the glass has not been tested for possible coesite. No rim remains - its position might well be marked by a depression. The crater is clearly a feature superimposed on a large regional syncline plunging about  $20^{\circ}$  to  $S30^{\circ}E$ .

Potash feldspars of unusually low optic angle are present in the rim rocks south of the Brent crater. Preliminary studies suggest there is a shock induced disordered state within the feldspar crystal, which in the extreme case produces feldspar glass with a higher refractive index than quenched feldspar glass. Microprobe and structural state studies of these feldspars are in progress.

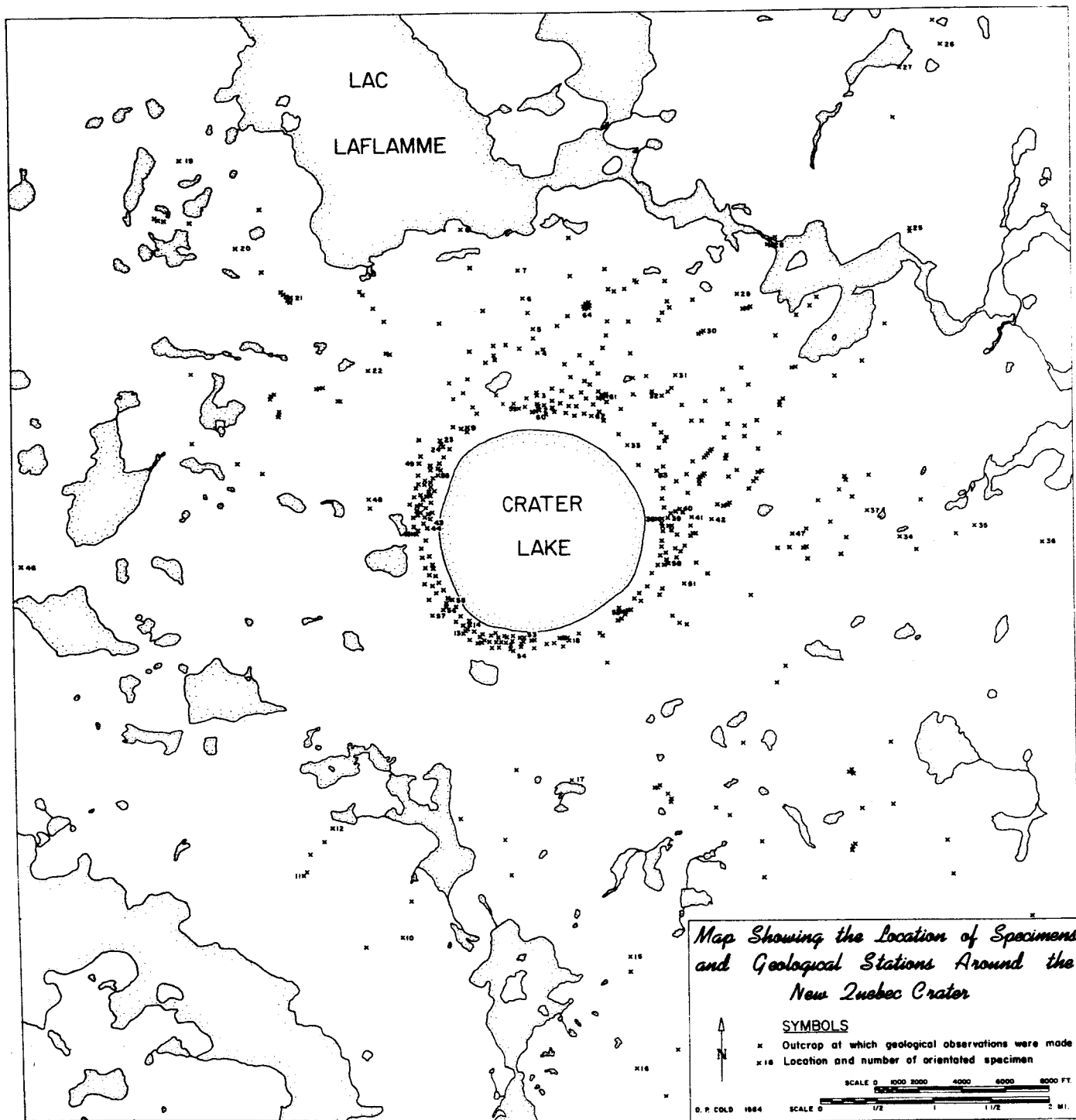
## PERSONNEL

The principal investigator is Professor O. F. Tuttle, with Professors V. Vand, and P. J. Wyllie available for consultation. Dr. D. P. Gold joined the project as a Research Associate in May, 1964, and currently is co-ordinating the research projects and compiling the results of the summers' field work. The overall project is being directed by Professor Tuttle. Mr. B. Robertson, an MS candidate is working up the general petrology of the areas investigated, and the petrology, mineralogy, and deformation features of the Lac Couture breccias. The breccias are being searched for coesite by x-ray, optical and chemical means. Mr. Robertson intends to submit a thesis embodying the above investigation for the summer commencement (September, 1965). Mr. F. K. Aitken, who started his MS program during the Fall Term and will slant his thesis towards the structural geometry and mechanisms of formation of the craters, currently is investigating the feasibility of using thermoluminescence and/or photoelastic techniques for measuring the strain in the rocks and thence deducing the stress distribution attendant with cratering.

THE GEOLOGY AND STRUCTURE AROUND THE NEW QUEBEC CRATER  
(Latitude 61 17'N, longitude 73 42'W)

The New Quebec crater is a rimmed crater, almost completely circular, with a lake in the crater depression. The mean lake diameter is 9430 feet; the mean rim (top of rim) diameter is 11290 feet. The highest point on the rim is 2156 feet, the lowest 1810 feet, with a mean rim height above the lake of 360 feet and a maximum height of 536 feet. The depth of the lake is 825 feet, the surface elevation 1620 feet is lower than that of the surrounding small lakes which lie on a surface of about 1650 feet elevation, but is on par with the large lakes a little farther out. The crater rim, which rises some 600 feet above an otherwise monotonous regional erosion surface (plane of about 1550 feet elevation) covered with glacial rubble and muskeg, is the most prominent feature on the New Quebec plateau. The rim, which has an inward slope of  $30^{\circ}$  to  $38^{\circ}$  and a gently dipping outer slope of about  $8.5^{\circ}$  (Millman, 1956), is underlain by bedrock which is mostly covered with a veneer of rubble.

Archean rocks, consisting of 'granite, biotite granite, granite gneiss, granodiorite, biotite gneiss and a few lenses of amphibolite' (Beall, 1960), underlie most of the region. Proterozoic rocks of the Cape Smith-Wakeham Bay syncline are exposed near the Povungnituk River about ten miles to the north of the crater. The topography slopes gently to the north from the crater into the broad, shallow valley of the Povungnituk River, then rises into a series of parallel ridges which generally trend east, but which in places, show the effects of complex folding.





The prevailing direction of Pleistocene glaciation is from and to the east-northeast, though there is some evidence of at least one phase from the northwest. Rocks of the Cape Smith-Wakeham Bay belt, leuco-basalts, serpentinites, peridotites and gabbros of the Chukotat Group (upper), and siliceous dolomite, quartzite, 'iron formation', and metagabbro of the Povungnituk Group (lower), were recognized in the ablation moraine, felsenmeer, and rubble found surrounding, on the rim and within the crater, as were some boulders of post-Cape Smith belt porphyritic diabase. The presence of erratics on, about, and in the crater, of glacial scour marks on the rim and of whale-backs ( $045^{\circ}$ ) on the flank of the eastern rim, attest to the pre-glacial origin of the crater. The New Quebec ice center lay in this general area, which accounts for the lack of marked glacial erosion or deposition.

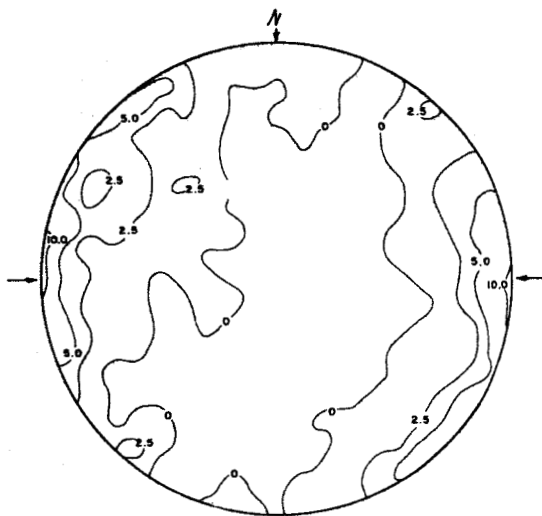
#### Rock types and structure

Acid Archean gneisses underlie the area surrounded by the crater, and except for a small diabase dike three miles east of the crater center and another near Lac Laflamme no manifestations of igneous activity were observed. The bedrock consists mainly of quartz-feldspar biotite gneiss, with lesser amounts of quartzofeldspathic gneiss, granite gneiss, biotite gneiss, augen gneiss, quartz-feldspar-hornblende gneiss and enclaves, boudins, rods and pods of amphibolite. In places, rusty weathering sheared gneiss, rich in sericite are exposed. Cataclastic augen gneisses probably represent incipient shear zones.

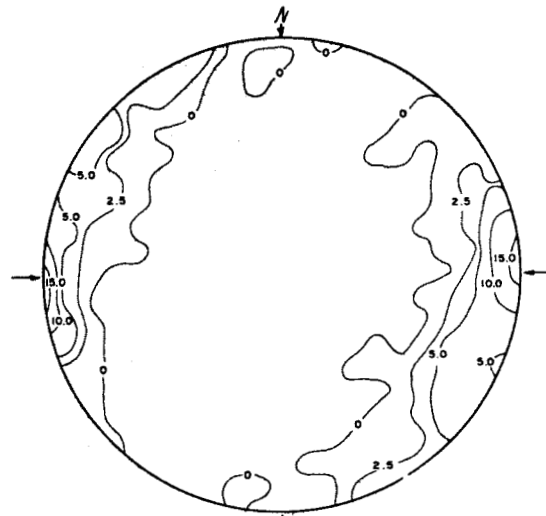
The gneissosity (primary foliation and gneissic banding) has

## FIGURES

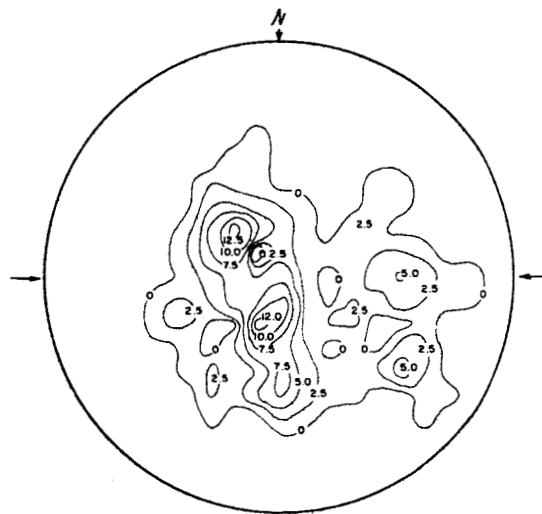
- 1A -  $\pi$ -diagram showing the primary foliation of the  
Rim Rocks. (204 points).
- 1B -  $\pi$ -diagram showing the primary foliation of the  
Country Rocks. (128 points).
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- 2B -  $\beta$ -diagram showing the penetrative lineation, 'b',  
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- 3A -  $\pi$ -diagram of joint planes (excluding sheeting joints)  
of the Rim Rocks. (635 points).
- 3B -  $\pi$ -diagram of joint planes (excluding sheeting joints)  
of the Country Rocks. (482 points).
- 4A -  $\pi$ -diagram of sheeting joints in the Rim Rocks.  
(227 points).
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(123 points).



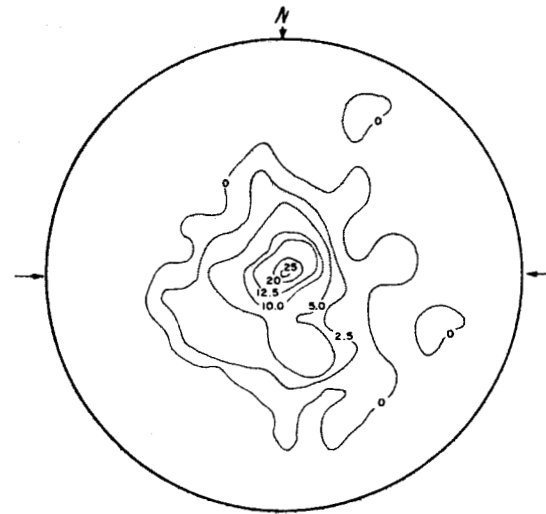
1a Contours: 0-2.5-5.0-10% per 1% area



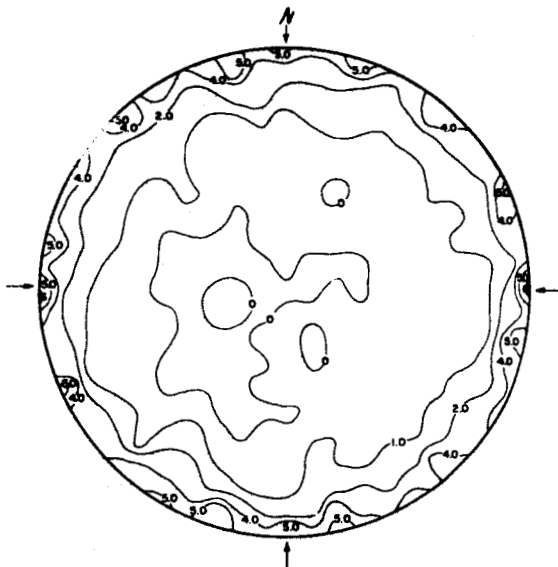
1b Contours: 0-2.5-5-10-15% per 1% area



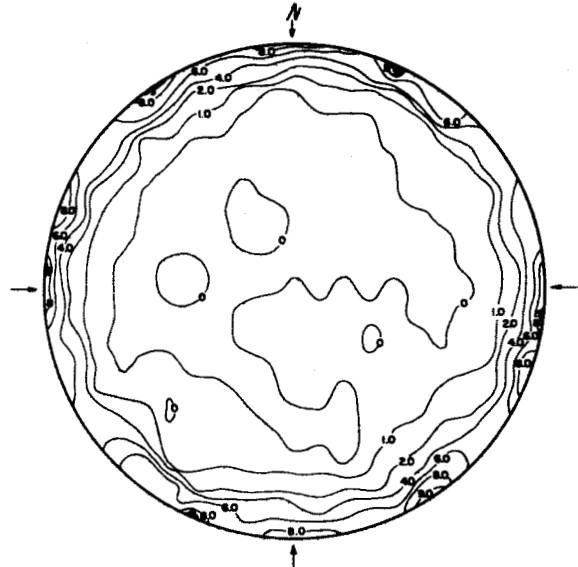
2a Contours: 0-2.5-5-7.5-10-12.5% per 1% area



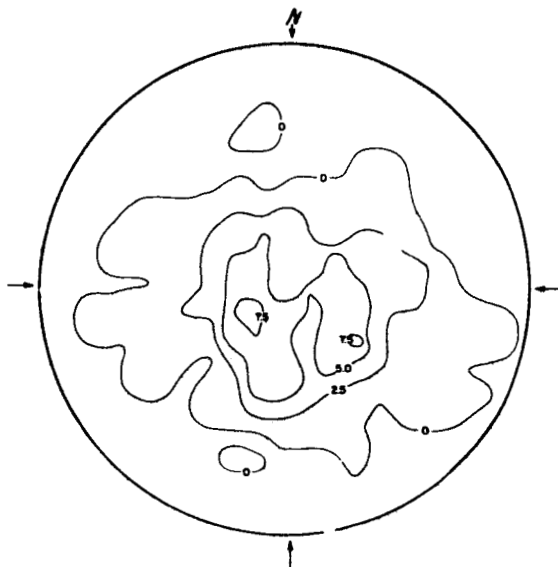
2b Contours: 0-2.5-5-10-12.5-20-25% per 1% area



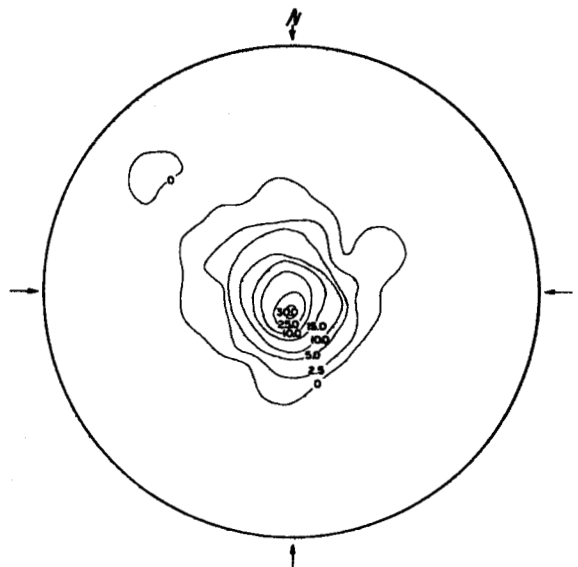
3a Contours: 0-1-2-4-6 % per 1 % area



3b Contours: 0-1-2-4-6-8-9 % per 1 % area



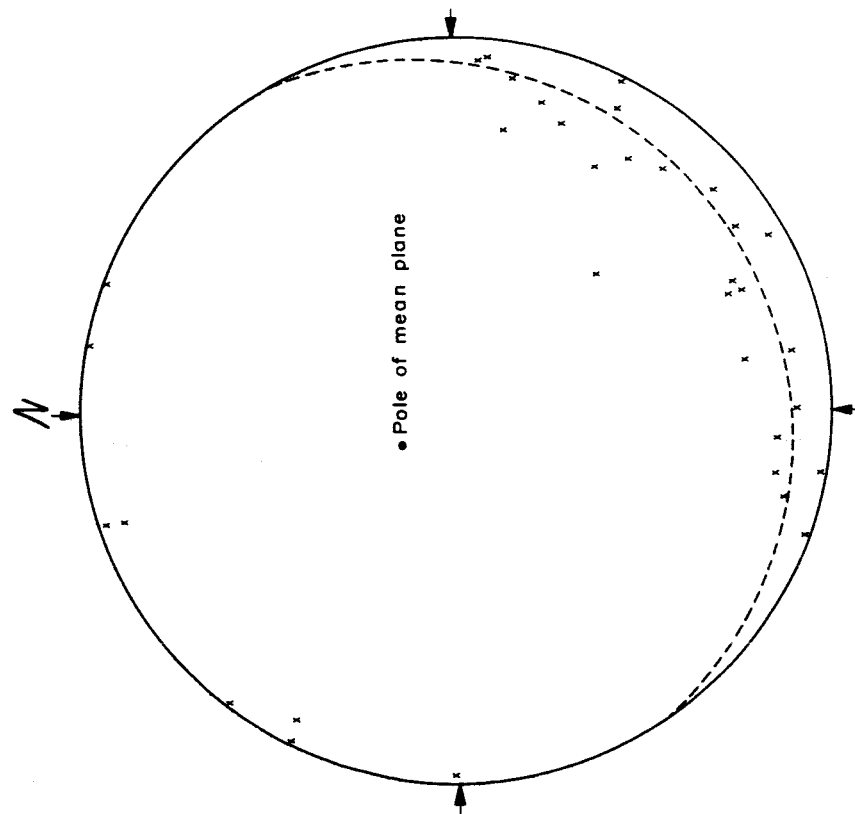
4a Contours: 0-2.5-5-7.5 % per 1 % area



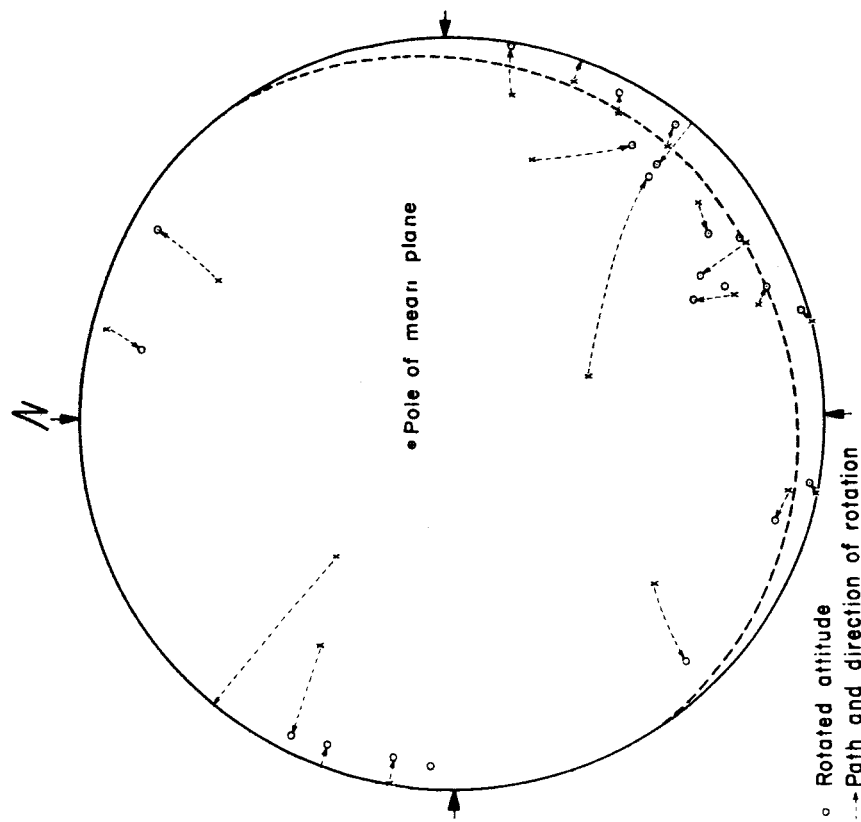
4b Contours: 0-2.5-5-10-15-25-30 % per 1 % area

a general strike of  $N25^{\circ}E$  and dips steeply to east and west. In figure 1b it should be noted that the maximum corresponds to a N-S strike. By comparison (figure 1a) the foliation in the rim rocks, while having the same general strike, have a greater variation of dip. The penetrative lineation 'b', was measured on the following features: axes of drag and minor folds, rodding of the quartzo-feldspathic bands and of the amphibolite schlieren, boudins and elongate pods of amphibolite, and the alignment of mineral grains on foliation planes. Statistically, these have a plunge of  $85^{\circ}$  to  $S20^{\circ}W$  for the country rock (figure 2b), whereas for the rim rocks minor maxima are scattered over a broad domain (figure 2a). A second 'S' plane, (shear foliation), cutting the primary foliation was seen in most shear zones. In places, the primary foliation was completely superimposed, and the original biotite converted into sericite. In and near these zones an 'a' lineation is developed. A spherical plot of the shear planes in the country rocks (figure a, plate 2) shows them to be fairly consistent and to lie near a great circle defining a mean plane of  $N58^{\circ}E$  strike and  $78^{\circ}NE$  dip. As for the plots for the other structural elements, the shear planes in the rim rocks have a more random attitude (see figure b, plate 2).

The overall structure of the country rock is interpreted as a series of steeply inclined isoclinal folds (see figures 1a, 1b), plunging steeply south-southwest. This folding pattern is in agreement with the work of Currie (1964), but at variance with his map (1964, p. 97), which he developed using the following lithologic units: granitoid plutonic rocks, granite gneiss, and agmatite.



a. Point diagram showing poles of shear planes in country rocks



○ Rotated attitude  
 --- Path and direction of rotation

b. Point diagram showing the poles of rim shears corrected for inclination of sheeting joints

In places epidote is common, with perhaps a greater amount in the rim rocks than in the country rocks. Epidote is not unique to the crater area, but occurs throughout the granite gneiss terrains of Northern Quebec (Kretz, 1960).

Smooth, flat and curvilinear fracture planes (usually almost normal to the 'b' lineation), spaced about a yard apart, are ubiquitous. These sheeting joints have a subhorizontal attitude (dip randomly at low angles, usually less than  $10^{\circ}$ , rarely over  $30^{\circ}$ ) in the country rocks, whereas in the rim rocks they have an outward dipping attitude pattern, as in a dome. Generally, steeper dips prevail towards the center becoming progressively shallower outward. On the rim the dips vary from  $10^{\circ}$  inward to  $80^{\circ}$  outward, and in the steeply inclined sectors use is made of the 'b' lineation to define the sheeting joint. Currie and Dence (1963) plotted the dip vector on a radial diagram and showed 'the sheeting dipping away from the crater with a crude bilateral symmetry, about a northwest trending axis'. The absence of any relationship between the symmetry axis to the foliation or joint systems led them to conclude that the deformation was formed by an 'explosive event' ... 'about an inclined line'.

Steeply inclined joint planes are numerous in both the rim rocks and the country rocks. The most prominent joint sets in the country rocks strike  $005^{\circ}$ ,  $020^{\circ}$ ,  $045^{\circ}$ ,  $085^{\circ}$ , and  $115^{\circ}$  true respectively (see figure 3b), whereas for the rim rocks they strike  $000^{\circ}$ ,  $022^{\circ}$ ,  $046^{\circ}$ ,  $060^{\circ}$ ,  $076^{\circ}$ ,  $090^{\circ}$ ,  $108^{\circ}$ ,  $130^{\circ}$ ,  $155^{\circ}$  true respectively (see figure 3a). While a girdle is present in the country rock joint pattern, the major sets correspond to two sets of

conjugate joints about the fold axis and one set parallel to it. For the rim rocks the girdle is more real, implying a more homogeneous joint pattern. In the field these are seen to be a conjugate set, approximately  $45^{\circ}$  to the radius, a set parallel to the radius, and a concentric set perpendicular to the radius. There appears to be some superposition of 'crater' joints into the country rocks (compare figures 3a and 3b), which suggests that jointing is the most sensitive deformation structure produced during crater formation.

### Structural analysis

The bedrock rim, which rises 1300 feet above the floor of the lake and some 300 to 500 feet above the surrounding plane, exhibits no additional deformation features not present in the country rock, except inclined sheeting joints, an increase in the incidence of joints, and a mylonite seam near the north beacon (concentric to and dipping towards the crater at  $60^{\circ}$ ).

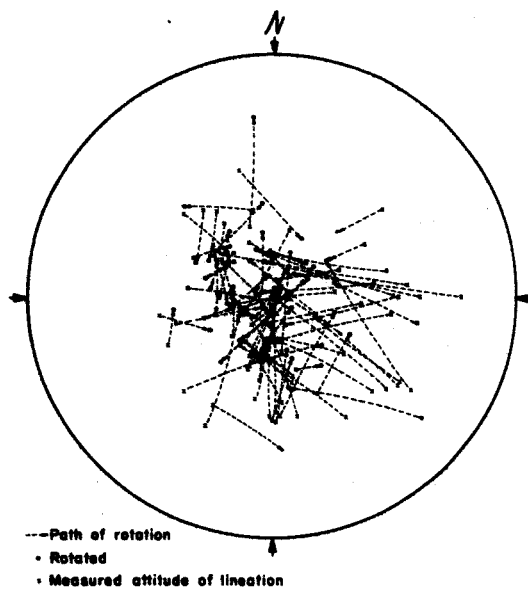
Because of the absence of any marker beds, it was necessary to establish whether the sheeting joints were pre-crater in age and of similar origin to those developed in the country rocks. If so they could then be used as a control horizon. If the stereographic plots ( $\beta$  and  $\pi$  contoured diagrams) for the attitudes of the primary foliation, penetrative lineation, and sheeting joints for the rim rocks (figures 1a, 2a, 4a) are compared with the corresponding diagrams (figures 1b, 2b, 4b) for the country rocks, a scatter of the points is evident. When the structural elements (foliation and lineation) are corrected for the amount of dip of the sheeting joints (for a set of readings from an individual



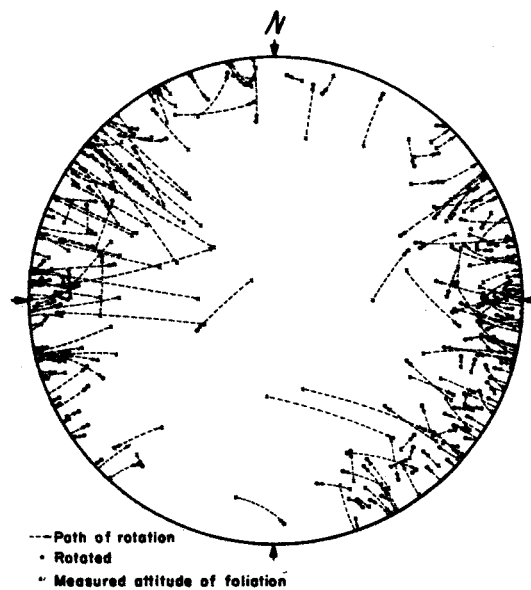
## FIGURES

Correction of attitudes of structural elements as sheeting joints are rotated to a horizontal position.

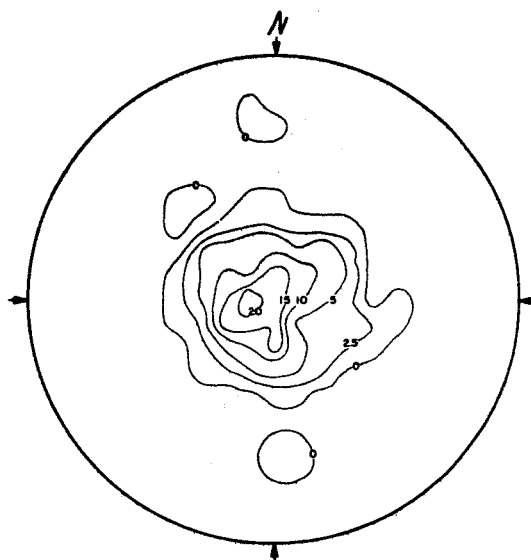
- 1A - Point diagram showing the path and amount of rotation of the penetrative lineation, 'b', of the Rim Rocks as they are rotated with their corresponding sheeting joints.
- 1B - Point diagram showing the path and amount of rotation of the primary foliation of the Rim Rocks as they are rotated with their corresponding sheeting joints.
- 2A -  $\beta$ -diagram of the rotated attitudes of the penetrative lineations, 'b', of the Rim Rocks. (82 points).
- 2B -  $\pi$ -diagram of the rotated attitudes of the primary foliation of the Rim Rocks. (200 points).



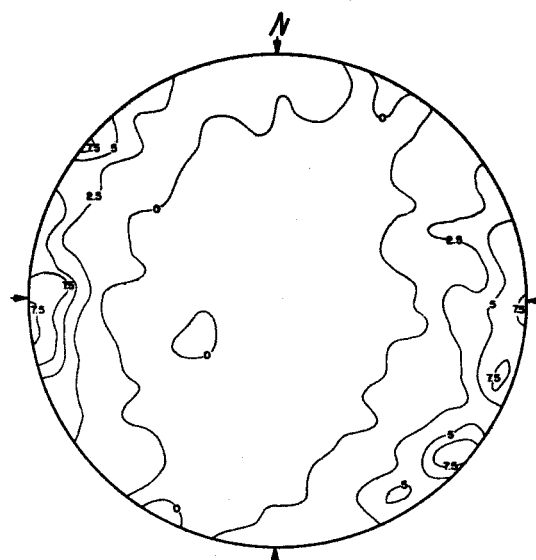
1a.



1b.



2a. Contours 0-2.5-5-10-15-20% per 1% area



2b. Contours 0-2.5-5-7.5 % per 1% area

outcrop, the attitude of foliation and lineation are rotated by the amount of dip in the dip plane of the sheeting joint as it is rotated to a horizontal attitude - see figures 1a and b, 2a and b, plate 3), then their statistical attitudes are almost identical with those for the country rocks (compare figures 2a and b, plate 3, with figures 1b and 2b, plate 1). This appears sufficient proof to justify the use of sheeting planes as a horizontal control for model analysis.

The shear planes in the rim rocks likewise can be rotated to correct for the amount of tilt (figure b, plate 2). This produces a mean plane of strike  $N56^{\circ}E$  and dip  $80^{\circ}NE$ , which is almost identical with that of the shear planes in the country rock ( $N58^{\circ}E$ , dip  $78^{\circ}NE$ ). While it is realized that there are too few points to make a good statistical plot, the inference is that the shear zones on the rim are pre-crater in origin. No doubt some movement during cratering took place along these planes.

### Conclusions

1. Sheeting joints in the rim rocks pre-date the crater and are similar in origin to those in the country rocks.
2. Because sheeting joints are considered to be a shallow manifestation very little erosion has taken place since crater formation.
3. The age of the crater is post-dabase intrusion (Proterozoic), pre-Pleistocene glaciation, and by virtue of its preserved profile, it is thought to be close to the latter age.
4. The absence of any volcanic material or structures (radial,

concentric, ring dikes, and cone-sheets etc.), the isolation from volcanic centers, the absence of vortex structures in the host gneiss and the clear superposition of the crater on the regional structure, the height of the rim and absence of shattering indicating a plastic rebound, are consistent with a meteorite impact origin for the crater.

5. A diamond drill-hole should be drilled through the center of the crater when and if equipment capable of doing this are developed.

## GEOLOGY AND STRUCTURE AROUND THE LAC COUTURE CRATER

The map encompasses an area 28 miles by 25 miles about the center of Lac Couture, which is located at approximately  $60^{\circ} 08' N$  latitude, and  $75^{\circ} 18' W$  longitude, in Northern Quebec. The lake has a roughly circular outline, about 9 miles in diameter, with many islands in the peripheral region. An island-free circle of 6 miles diameter can be drawn in the central portion. The lake forms part of a southerly flowing drainage system which ultimately drains eastward into the Payne River. The lake is distinctive in an area of numerous lakes (which generally have irregular outlines and whose shape reflects the bedrock joint pattern), by virtue of its size and shape. Unfortunately, no adequate topographic maps are available, but the ground rises gradually from the lake (440 feet above sea level) and then fairly steeply to about 650 feet at a distance of 5 to 6 miles from the center. About 10 miles out, in a northeasterly direction, the surface elevation is about 830 feet.

Lac Couture is situated in the 'low arctic tundra', climatic zone. The regional movement of the Pleistocene and Recent ice sheets is in direction from  $N85^{\circ}W$  to  $N60^{\circ}W$  (Kretz, 1960); the local movement, as measured from eskers and glacial striae, is almost due west. The amount of local glacial erosion is not known: glacial deposition is restricted to four eskers, an outwash fan, and a ubiquitous thin veneer of ablation moraine. Farther west (out of the map area), outwash fans and pro-glacial deposits are more abundant. Erratic of a polymict breccia are restricted to a fan, and the esker, which extends westward from the lake (see

map 1). The breccias obviously underlie Lac Couture; the erratics represent a unique sampling of the lake floor.

There is no obvious topographic manifestation of a rim. If the innermost islands represent the remains of a rim, then an annular depression exists between those islands and the shore. A good topographic map is needed, before any profiles can be deduced.

Orientated specimens and geologic observations were made for distances of 13 miles east of, 7 miles south of, 9 miles west of, and 9 miles north of the center of Lac Couture, and on selected islands within the lake (see map 1). The bedrock consists mainly of massive granitic gneiss and coarse-grained quartz-feldspar-biotite gneiss, with lesser amounts of quartz-feldspar-epitote gneiss, quartz-feldspar-mica schist, enclaves and schlieren of amphibolite. Those valleys, which coincide with prominent lineaments, are commonly underlain by schist, whereas the ridges are generally formed of quartz-feldsparitic gneisses and pegmatite. Diabase dikes, varying in thickness from a few inches to a few hundred feet, trend in two main directions, southeast and south  $75^{\circ}$  east. They appear to be more abundant in the northern portion of the area than the southern, and are apparently related to the Klotz Lake-Lac Nantais dike swarm exposed 48 miles to the northeast (Kretz, 1960). The dikes have an en echelon pattern, offset to the left: many bifurcate. Thin veins and seams of epidote were found in almost every outcrop on which detailed observations were made. The attitude of these 'seams' appears to be unsystematic.

The breccia erratics are rough-pitted, irregular blocks scattered on the tundra. They vary in size from 6 to 10 feet

across on the islands in the lake to progressively smaller fragments (hand specimen size 9 miles out) farther out. Typically, they consist of angular fragments of country rocks in a matrix of comminuted rock fragments and kaolin. Commonly the kaolin is stained red. The fragments (excluding matrix) vary from 1/4 inch to 20 inches across, and are only of rocks typical to the country rocks. Many of the pebbles on a beach, located 5 miles due west of the center of Lac Couture, consist of microbreccia, glassy shards, and crypto-crystalline material (for details see the next section).

### Structure

The regional structure as deduced from the control traverses and an analysis of the aerial photographs (facilitated by the fact that the drainage pattern, lake outlines, and topography are strongly influenced by the bedrock structure) are summarized in map 2. The regional folds appear to be concentric in type, which is surprising for rocks which are considered to be part of the basement complex. The plunge varies from about  $10^{\circ}$  to  $60^{\circ}$  in a south-southeasterly direction, with a general value of  $40^{\circ}$ . Insufficient readings are available to determine whether or not these variations are meaningful.

Subhorizontal sheeting joints are ubiquitous; nearer the lake some flexed sheeting planes were observed. The vertical joint systems have yet to be analysed. Fracture patterns for the area were plotted from aerial photographs and were seen to correspond mainly to bedrock structures. However, there is a crude annularity to the first set of fractures outward from the lake, and because

many of these are roughly  $45^{\circ}$  to the radius it is thought that they may represent superimposed shear joints.

Two prominent lineaments are seen to extend from the southeast, disappear under the eastern portion of the lake, then continue to the northwest. These appear to represent shear zones associated with folding.

### Conclusion

1. The Lac Couture feature is a circular structure superimposed on a large anti- and syn-form plunging south-southeast at about  $40^{\circ}$ .
2. The circular feature represents a rimless crater, which is underlain by polymict breccias, one phase of which consists of glassy material.
3. Sufficient structural and petrological controls have been established, by sampling the country rocks, to note any meaningful changes in the rocks adjacent to and from (breccias) the crater.
4. By analogy with other circular structures on the Canadian Shield, the lack of radial dikes and volcanic material, the shocked nature of the breccias, it is concluded that the Lac Couture crater is of the meteorite impact type.
5. An integrated study, involving topographic mapping, glaciation, petrology, geochemistry, geophysics, and regional and local structure should be contemplated. (The estimated cost of such a field project for one field season, would be of the order of \$30,000).



## STUDIES ON THE LAC COUTURE BRECCIAS

### Deformation Planes in Quartz

During petrographic examination of thin sections of the breccia it was noted that those quartz grains with the highest interference colors, showed sets of dark parallel lines on their surface. Universal stage examination revealed that these are actually the traces of sets of planes within the quartz grains.

Planar features within quartz, termed Böhm lamellae or deformation lamellae, have been described by several authors. In a review of these lamellae, Christie and Raleigh (1959) recognize five different forms: (1) those consisting of 'minute closely-spaced inclusions'; (2) those composed 'partly, but not entirely, of inclusions'; (3) those not consisting of inclusions, but as narrow zones of a different refractive index from that of the host quartz grain; (4) those composed of 'planes of brown, sometimes liquid, inclusions, also showing a difference in refractive index'; (5) those 'consisting only of brownish granular material'. Ingerson and Tuttle (1945) described deformation lamellae as not being sharp, straight bands, but as slightly lens-shaped with a measurable thickness, and some or all of which pinch out before they reach the edge of the grain. By contrast, the planes under investigation in the Lac Couture breccias predominantly are sharp, narrow and straight, and although some do terminate in the middle of a grain, the majority extend to the margins. In continuity with other descriptions of deformation lamellae, these lamellae are restricted to a single grain, and do not continue into neighboring grains. The narrowness of these planes precludes (by simple optical means)

the detection of any differences in interference colors or refractive index from the host grain.

Two, and in places three or more, sets of planes with different orientations are present in a single grain. Although the entire grain is equally well transected by these planes, most grains with two or more sets show areas where one set predominates. The spacing between planes of a particular set varies, but averages less than 0.01 mm. For the most part, the planes are straight and parallel, but some show minor bending, and others exhibit a 'kink-band' type of pattern. No translation movement has been detected along any of these planes.

The relationship that deformation lamellae form approximately normal to bands of undulatory extinction, was noted by Mugge (Quoted from Christie and Raleigh, 1959), and is partially confirmed by observations on quartz grains in the Lac Couture breccias. These grains, in general, exhibit very pronounced undulatory extinction, and although the 'undulose bands' are not always normal to the lamellae, they do intersect at a fairly high angle.

The orientation of the deformation planes (lamellae) with respect to the crystallographic axes, was measured on a five-axis universal stage. Five thin sections yielded 117 quartz grains which either showed the traces of these planes on a 'flat stage', or brought the traces into view by a rotation about one or more of the horizontal axes of the universal stage. The angle between the c-axis and the pole to the deformation planes was measured for 201 sets of planes and plotted on a histogram (figure 1). According to Ingerson and Tuttle (1945), grains showing two or more sets of

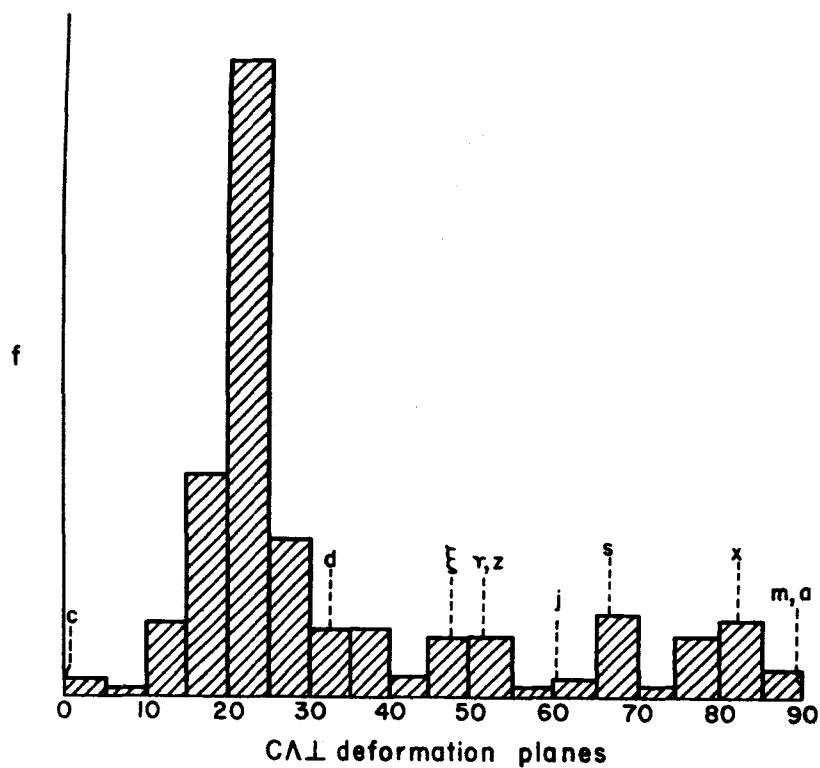


fig. 1. Histogram showing angular relationship between the poles to the deformation planes and the c-axis of the quartz grains in which they occur. Dotted extensions represent the angle between the normals to cleavage planes in quartz and the c-axis.

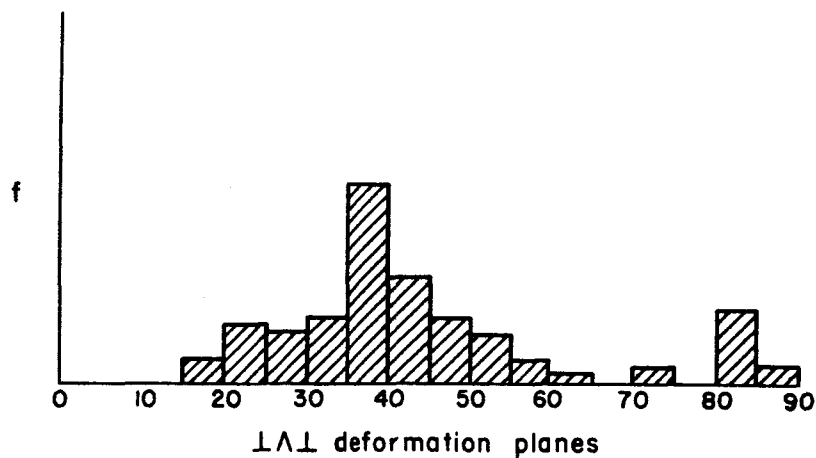


fig. 2. Histogram showing the interplanar angles for deformation planes in quartz.

deformation lamellae are comparatively rare. Of the 117 grains measured in this study, 63 showed two sets of deformation planes, 9 showed three sets, and one showed 4 different sets.

From figure 1 it is seen that the frequency maximum for  $c \perp$  deformation planes lies in the  $20.1^\circ$  to  $25.0^\circ$  class. Smaller modes occur for the  $45.1^\circ$  to  $50.0^\circ$ ,  $50.1^\circ$  to  $55.0^\circ$ ,  $65.1^\circ$  to  $70.0^\circ$ , and  $80.1^\circ$  to  $85.0^\circ$  classes. It is of interest to note that these 'minor' modes correspond to the angles formed by the c-axis and the poles to the  $\xi$ , r and Z,  $\lambda$ , and x cleavages respectively as reported by Bloss and Gibbs (1963). However, the relative frequencies of the deformation planes at these points do not agree with those of the corresponding cleavages. Bloss and Gibbs (1963) did not find any cleavage in quartz whose pole makes an angle of  $20.1^\circ$  to  $25.0^\circ$  with the c-axis. Bunch and Cohen (1964) likewise make no mention of such a cleavage. Several workers have made similar measurements for the angle between the c-axis and the normal to the deformation lamellae. These tend to be low angles, but the actual values vary considerably between  $10^\circ$  and  $30^\circ$ . Moreover, no correspondence between deformation lamellae and cleavage planes has been shown to exist.

Because the deformation planes lie at a high angle to the c-axis, it is now evident that their traces should be more easily visible on grains showing the highest interference colors.

The interplanar angles were measured and plotted on a histogram (figure 2). The result is a bimodal distribution with a maximum in the  $35.1^\circ$  to  $40.0^\circ$  class, and a smaller peak in the  $80.1^\circ$  to  $85.0^\circ$  class. This non-uniform distribution indicates a

definite tendency for these sets of planes to form at a preferred angle to each other. This suggests a strong crystallographic control; the deformation planes may be rational crystallographic planes. Certainly, those planes corresponding to the cleavages are rational, and are in fact cleavages planes. Frondel (1962) reports that a rare but authenticated cleavage form ( $10\bar{1}3$ ), designated as  $\psi$ , has been found in a few cases. The pole to this cleavage plane makes an angle of  $22^{\circ} 56'$  with the c-axis. The interplanar angle between  $\psi$  and one of its two companion faces ( $\bar{1}103$ ) and ( $0\bar{1}13$ ), based on trigonal symmetry, is  $39^{\circ}28'17''$ . These values lie within the maximum classes of figures 1 and 2 respectively.

#### Conclusion:

The descriptive and measured characteristics of the deformation planes show that they are, at least partially, crystallographically controlled. These same characteristics do not seem to match those described by other authors as belonging to the deformation lamellae or Böhm lamellae. Because these planes occur in highly deformed rocks, it is not unreasonable to assume that high pressure has played an important part in their formation.

#### Petrology of the Lac Couture breccias

Apart from some small pebbles of glassy material and a few small shards of glass, no glass has been found in any of the large breccia blocks, though the matrix of a number of these specimens show devitrification type textures. Various stages of 'devitrification', from cryptocrystalline (as yet unidentified) material, spherulites of feldspar and silica, to a felty textured matrix

of feldspar laths, have been found. Vugs, containing crypto-crystalline material, chalcedony, and a zeolite (?), are present in the coarse breccias. Two ages of vugs are apparent in some thin sections, one of which is deformed and the other undeformed.

## INVESTIGATIONS FOR COESITE AND STISHOVITE

A search for coesite and stishovite is being carried out on breccia float fragments and on small glassy pebbles from the Lac Couture crater, and on mylonite, fault breccia, and friction breccia from various localities (mainly in eastern Canada). Forty hand specimen size samples were crushed in three stages to about -200 mesh size. In addition, for control purposes, two samples of suiveite from the Ries Kessel (which are known to contain coesite), plus a 'typical' granodiorite sample (known to be barren of coesite), were crushed in the same manner.

Ten grams of each sample were weighed out and ground in a mullite mortar and pestle until no 'gritty feel' remained. The digestion procedure is modified from that used by the U.S.G.S. (personal communication, E. Chao, and J. Fahey).

### Procedure:

Digestion of each sample was carried out in 180 ml of 5% HF at room temperature, in a 250 ml teflon crucible. The volume of acid used is based on the amount required to dissolve all the silica, assuming each sample to contain 70%  $\text{SiO}_2$ . The digestion process took from 15 to 24 hours, after which, the acid was decanted off, leaving any dissolved material in the crucible. The residue was treated with an acid solution (20ml conc. HCL, plus 10 ml conc.  $\text{HNO}_3$ , plus 20 ml distilled  $\text{H}_2\text{O}$ ), in order to dissolve any uni- and di-valent cation silica-fluorides which might have formed, and left at room temperature for another 15 to 24 hours. This mixture was then filtered and the residue washed with distilled water and allowed to dry at room temperature. The

above processes were repeated (usually four times) until the original sample was reduced to less than 0.5 gram. The total time for a complete run varies between two and three weeks.

The residue is mounted on a glass slide then run on a x-ray diffraction unit. The diffraction pattern is compared with known patterns for coesite and stishovite, which were obtained from Dr. J. Fahey of the U.S.G.S.

#### Results:

Of some 12 Lac Couture samples that have been run, neither coesite nor stishovite has been detected. The granodiorite control was blank; the suiveite control contained coesite, but no stishovite was detected.

#### Conclusions:

1. Barren runs on the Lac Couture samples may reflect insufficient concentration of the high pressure forms in the residue.
2. Once the preliminary runs are completed, greater amounts of selected samples should be re-run with a greatly increased concentration factor.



## PLANNING FOR THE NEXT SIX MONTH PERIOD

The proposed schedule is largely an extension of the schedule outlined in the previous report, with some new directions which are a follow-up of the current work.

1. Continue with the microfabric analysis (deformation planes and planes of fluid inclusions in quartz) on the rocks from Brent, New Quebec, and Lac Couture, and to determine the orientation of these planes with respect to the crystallographic directions of the host.
2. Stain the above thin sections in order to distinguish the K-feldspar; measure the 2V angle of both K- and Na- feldspar, and plot contours of 2V (trend surfaces) about the craters.
3. Develop a simple chemical method for verifying the composition of the feldspars (the method currently employed of crushing, separating in heavy media, then preparing mounts for micro-probe work, is not only time consuming but also not very satisfactory).
4. Determine the structural state of the feldspars on profiles out from each of the craters.
5. Continue studies on the Lac Couture breccias (deformation lamellae, 2V of feldspars, nature of the glasses, etc.).
6. Continue with the petrographic descriptions of the areas surrounding respectively the Lac Couture and the New Quebec Craters.
7. Complete the structural analysis of the Lac Couture area.
8. Start thermoluminescence studies on some of the orientated specimens, and if feasible, measure the strain relief on the

same specimens by photo-elastic techniques.

9. Prepare some samples for paleomagnetic studies (the Dominion Observatory has consented to run these for us).

10. Continue testing the crushed samples for coesite and stishovite.

#### PAPERS PUBLISHED OR IN PREPARATION

Jahns, R. H., McKague, L., Tuttle, O. F. Microjointing in basement, Middle Rocky Mountains of Montana and Wyoming.

A discussion. Geol. Soc. Amer. (in press).

Gold, D. P. Structural Studies around the New Quebec Crater. (in preparation).

Robertson, B., Gold, D. P., Tuttle, O. F. Cleavages in Quartz from the Lac Couture Crater. (in preparation).

Robertson, B., Gold, D. P. Search for coesite from varied geologic environments. (in preparation).

## ACKNOWLEDGEMENTS

On behalf of the Crater Project I would like to acknowledge the help and support given by the following people and organizations: Drs. Beals, Innes, and Dence, of the Dominion Observatory, Ottawa, for making possible the investigation of these craters, and for supplying topographic maps of both Lac Couture and the New Quebec Crater. Dr. Ira Stevenson of the Geological Survey of Canada, for furnishing a topographic outline map of the Lac Couture region. Mr. P. Furneaux, of the Department of Northern Affairs, Povungnituk, for allowing my party to use their facilities and for monitoring our radio calls. Raglan Nickel Mines, Toronto, for use of their facilities at Raglan Lake, and for monitoring our radio calls. Mr. F. Thurston, of Asbestos Corporation (Asbestos Hill Project), Montreal, for air transport from Asbestos Hill to Frobisher Bay. Drs. E. Chao, and J. Fahey, of the United States Geological Survey, Washington, for supplying x-ray powder patterns for coesite and stishovite, and the techniques for their concentration and detection. National Aeronautics and Space Administration, Washington, for sponsoring the project.

David P. Gold

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## APPENDIX I

### SUMMARY OF THE SUMMER FIELD PROJECT IN NORTHERN QUEBEC

The summer field work was completed with but little deviation from the planned schedule (as outlined in the previous report). This was gratifying in view of the number of variables involved.

The field party, consisting of Gold, Robertson and Aitken, staged in Montreal on July 13 and flew to Great Whale River on July 14 on Nordair Flight No. 51. A last minute switch in aircraft from a D.C.4 to a C.46, meant that our freight, which was supposed to accompany us, was left in Montreal and did not arrive in Great Whale until the evening of July 18. In spite of earlier bookings on Austin Airways northbound flight for July 16, no seats were available. However, an additional flight to pick up the excess, was made on July 17 to Povungnituk. The Cessna 180 (on charter from Georgian Bay Airways) remained in Great Whale until our freight arrived from Montreal, and rendezvoused with the rest of the party on July 19, in Povungnituk. A camp was established on July 19, on a beach 2-1/2 miles to the north of Lac Couture.

Because of heavy ice conditions this year, neither of the supply ships (one due in on July 1, the second on July 14) had arrived, consequently no fresh supplies were available (a factor that should be considered for any future expeditions to this area). Ice was present over the central part of Lac Couture until July 25. Generally, the weather was fine, with only one day of rain and fog. Traverses were completed to the north, south, east, and west of the crater; and also specimens were collected from some of the islands around the perimeter of the crater lake. The only other

suitable site for a camp is located 2 miles due west of the lake on an inlet.

In spite of the prediction of an early break-up, most of the lakes on the higher ground to the north were still frozen over. The first flight to the New Quebec Crater area left during the late afternoon of July 28, but was unable to land on the crater or surrounding lakes, and landed instead on the Povungnituk River at Raglan Lake 29 miles northeast of the crater. During the following two days the rest of the crater party and supplies were ferried to the Raglan Lake camp, where fresh supplies were obtained, and also the services of a helicopter. A camp was established on July 31 near the lake, within the eastern rim of the crater (this is the only suitable site within the crater).

Apart from a seven day period of strong wind and fog, the weather conditions were exceptionally good. The field work around the crater was completed in three main phases. The first phase consisted of 8 radial traverses  $45^{\circ}$  apart carried for a distance of five miles from the crater rim. Orientated specimens were taken approximately every half mile nearer the rim, and every mile farther out. Phase two consisted of 27 radial traverses, spaced 1000 feet apart on the rim and broadening to 1/2 mile apart 2 miles out, which filled in the gaps between and were run concurrent with the phase one traverses. On the phase two traverses geological and structural observations were made, and where necessary, samples were collected. The gaps between the 35 phase one and two traverse lines were plugged with phase three traverses every 300 feet along the entire perimeter of the rim. In the process every outcrop on

the rim was visited, except where extensive outcrop was exposed, which was sampled on a grid. Orientated specimens of the rim rocks were collected. Finally, some time was spent in those areas in the surrounding country where abundant and/or continuous bedrock was exposed.

During the evening of August 21, the party left by helicopter for Raglan Lake camp, thence to Asbestos Hill airstrip, where it was picked up by a D.C.3 aircraft (on charter to Asbestos Corporation) and flown to Frobisher Bay, Baffin Island (Asbestos Corporation waived charges for this flight, because of the academic nature of our work). The party returned on August 26 to Montreal on the Nordair schedule flight from Frobisher Bay. The outward trip was accomplished in deteriorating weather conditions, and it was more good luck than good management that there were no lengthy delays.

### Conclusions

1. The New Quebec Crater has been carefully and thoroughly sampled. Additional work here would be warranted only if drilling were contemplated.
2. The New Quebec Crater lake was free from ice on August 15, with new ice starting to form on August 21. Any future expeditions should not depend solely on this lake as their means of access.
3. The preliminary work on Lac Couture is encouraging. The use of the float plane for getting to strategic stops was restricted by swell or ice conditions. Any future field party should take in canoes and outboard motors. These would facilitate the mapping

of the islands, and the traverses inland from the perimeter of the lake.

4. A good topographic map, with depth soundings of the lake bottom, followed up by geological field mapping, is needed for the Lac Couture area.

5. The desolate country-side (barren lands), coupled with the 'isolation factor' encountered at Lac Couture, especially when working in areas surrounded by water, is the closest simulation of isolation I can think of to possible conditions on the moon. One is entirely dependent on one's transporting vehicle for survival. I recommend that this area be considered as a possible training ground for lunar astronauts (the abundant water is obviously a misrepresentation, but here it is a liability and not an asset).



## APPENDIX II

### COLLECTION OF ORIENTED SPECIMENS IN KOFELS CRATER IN OETZTAL, AUSTRIA - V. Vand, June 24 - 29, 1964

Method of collection: The specimens were, whenever possible, broken off the solid rock at the deepest point possible (water stream cut or road cut). They were then replaced and magnetic North marked on the upper surface with an arrow pointing to the North. Then a horizontal plane has been established by means of a spirit level and marked on the exposed surface of the rock. The rock was then removed and the horizontal marking completed at the rear surface, forming thus a continuous ring round the specimen.

In order to mark provisional center of the crater, a point 1 km southeast from the main church at Koefels has been chosen as a working center of the crater, lying on the northeast bend of the road from Koefels to Winkl.

The rock is mostly fine-grained gneiss, so cracked near the crater that it was difficult to collect large specimens of orientated rock, as these broke in smaller pieces.

Some loosely lying specimens were also collected in the crater. It is difficult to establish whether some of the exposed rocks were undisplaced by the explosion, or shifted and rotated by the blast. On the other hand, the propagation of shock wave through a valley and mountains may be complicated, so that some rocks on the opposite side of the valley, although near the crater, may have not suffered similar shock to those on the same side of the valley, although at the same distance from the center. This may complicate the interpretation of the results.

The position of the crater center is only a guess and is used only as an indication for the preliminary results.

The directions from center were taken from 1 : 25000 map and are counted from N or S ( $0^{\circ}$ ) toward E or W ( $90^{\circ}$ ).

Koefels crater is of about 3 km diameter (1.5 km radius) situated at  $47^{\circ} 07' N$ ,  $10^{\circ} 56' E$  on the W slope of the glaciation valley of Oetztaler Ache. The center is 1400 m altitude and is cut through a canyon called Maurach, which has an altitude 1050 m above sea level. The breccia has been thrown across the valley, forming Taufererberg. Glacial moraine is present under this breccia, suggesting the age of the crater as less than 10000 years.

#### Summary of localities

##### Specimen number

##### Description and location

- |     |  |
|-----|--|
| K01 | At small waterfall 1200 m SE from the main Umhausen church 2500 m $N32^{\circ}E$ from center   |
| K02 | At the S side of the same waterfall<br>2500 m $N32^{\circ}E$ from center   |
| K03 | At rock face by Waldcafe Stubobele under the great waterfall (Stubenfall) 2100 m $N44^{\circ}E$ from center  |
| K04 | Part of ejected boulder on top of Schartle (2088m altitude) which shows a white surface shock layer<br>2200 m $N87^{\circ}W$ from center (almost true W) |
| K05 | From vertical cliff on Schartle facing Koefels<br>2100 m $N85^{\circ}W$ from center  |
| K06 | On way from Schartle to Koefels nearest outcrop to center which still looks as solid rock in situ<br>1400 m $N87^{\circ}W$ from center                   |
| K07 | Loose iron-containing piece on the footpath. Should be analysed for presence of Ni.<br>1300 m $N80^{\circ}W$ from center                                 |

- K08 Loose iron-containing piece on the bank of the road  
1100 m N75°W from center
- K09 Loose reddish gneiss with white shock zone. (This  
coloration is rare) All loose specimens were collected  
(up to K 17) on the path to Schartle above the village  
of Kofels, where many shocked rocks occur with a white  
outer zone. All at about 1100m N75°W from center
- K10 Gneiss with white shocked zone
- K11 Similar to above.
- K12 " " " . Has a lot of quartz
- K13 " " "
- K14 " " "
- K15 " " " , but shows some flow pattern? Rarer.
- K16 " " "
- K17 " " " , but shows some flow pattern?
- K18 From first quarry in Maurach, where rockflour occurs.  
1100 m N24°E from center. Difficult to find larger  
specimens, as these fall apart.
- K19 Next stony outcrop at the left side of the road from  
Umhausen to Au. The outcrop looks like a giant  
shattercone. One surface of the specimen is the surface  
of the shattercone. 850 m N45°E from center.
- K20 By the first main road bridge. Surface of shattercone?  
850 m N60°E from center.
- K21 Typical "shattercone" slice halfway between first bridge  
and tunnel entrance. 650 m N68°E from center
- K22 First solid rock on the main road toward Au outside  
crater. Above the chapel. 2400 m S69°E from center.
- K23 Solid rock by Wiesle. 2800 m S86°E from center (almost  
true E)
- K24 Solid rock in road cut from Winkl to Wurzbergeralm.  
2000 m S23°E from center
- K25 Good rock from bottom of a gully opposite Umhausen  
1850 m N15°W from center.
- K26 Good rock from road cut on way to Erlanger Htt.  
2850 m N17°W from center.

Notice.

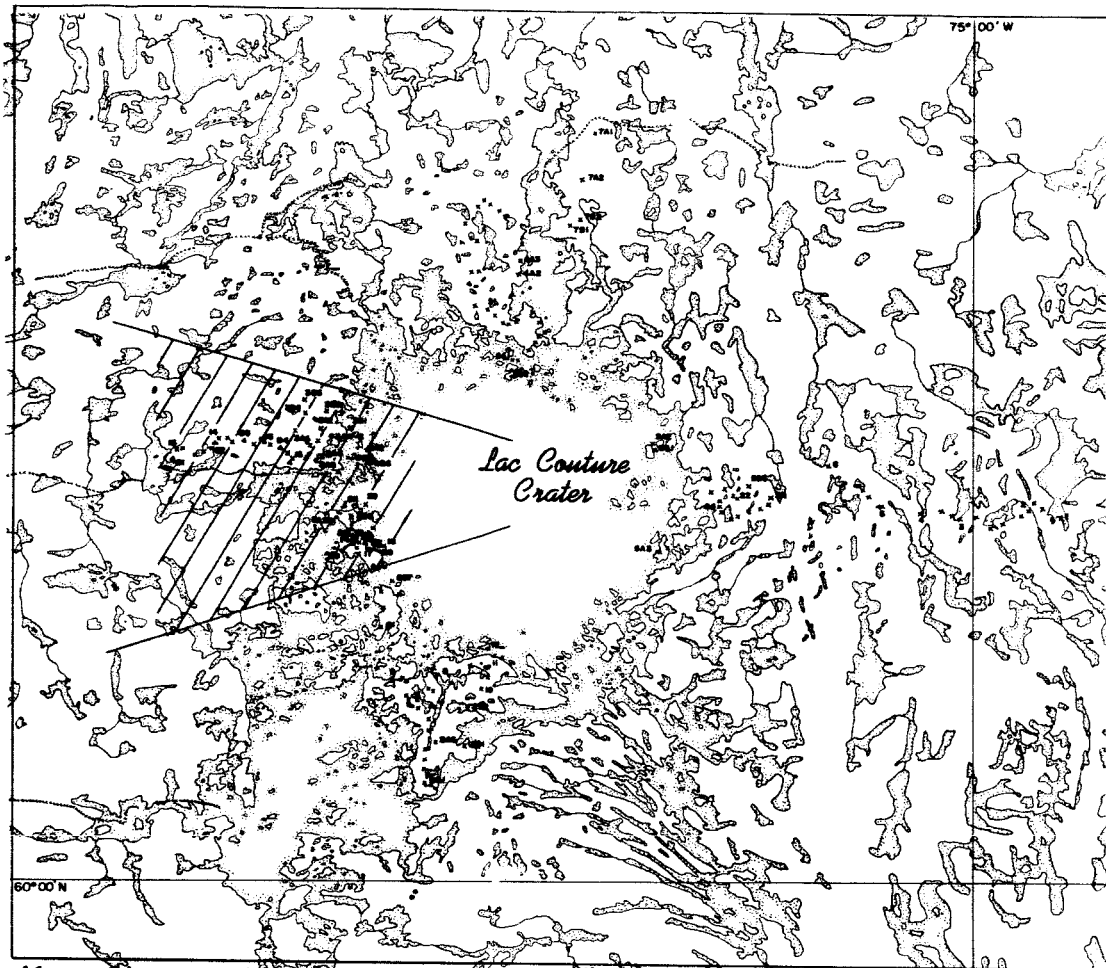
The accompanying maps should be included with the Second Annual Report covering the period January 1964 to December 1964.

1. 'Map Showing the Location of Specimens and Geological Stations around the Lac Couture Crater, Quebec', should be included as page following 'GEOLOGY AND STRUCTURE AROUND THE LAC COUTURE CRATER'.
2. 'Air Photo Interpretation of the Structural Geology for the Area Surrounding the Lac Couture Crater, Quebec', should be included two pages farther on, ie., page after subsection titled 'Structure'.
3. 'Map Showing the Location of Specimens and Some Geology of the Köfels Crater, Otztal, Austria', is the last page of APPENDI. II, ie., last page of the report.

I hope these maps can be conveniently and correctly placed.

Yours truly,

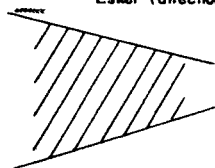
David P. Gold.



*Map Showing the Location of Specimens and Geological Stations around the  
Lac Conture Crater, Quebec.*

**SYMBOLS**

- x Outcrop at which geological observations were made.
- x<sub>AS1</sub>, x<sub>18</sub> Location and number of specimen
- A<sub>88</sub> Location and number of breccia sample (from float)
- Es<sub>1</sub> Esker (direction of transportation of material) ←



Area in which breccia float was found.

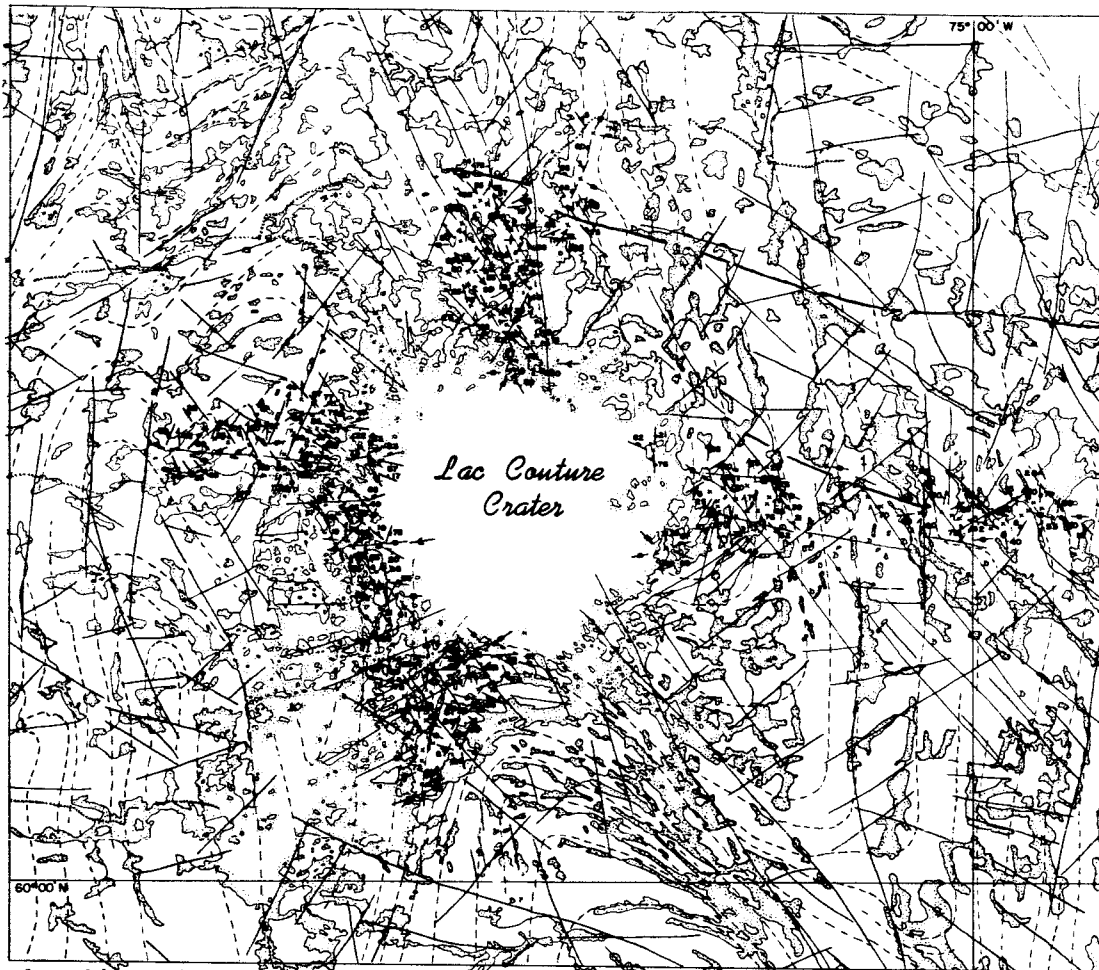


Lake



Scale 0 1 2 3 4 5 Miles

D. P. Gold, 1964



*Air Photo Interpretation of the Structural Geology for the Area Surrounding the Lac Couture Crater, Quebec.*

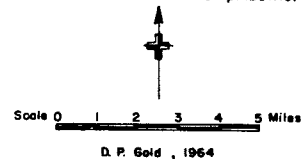
#### SYMBOLS

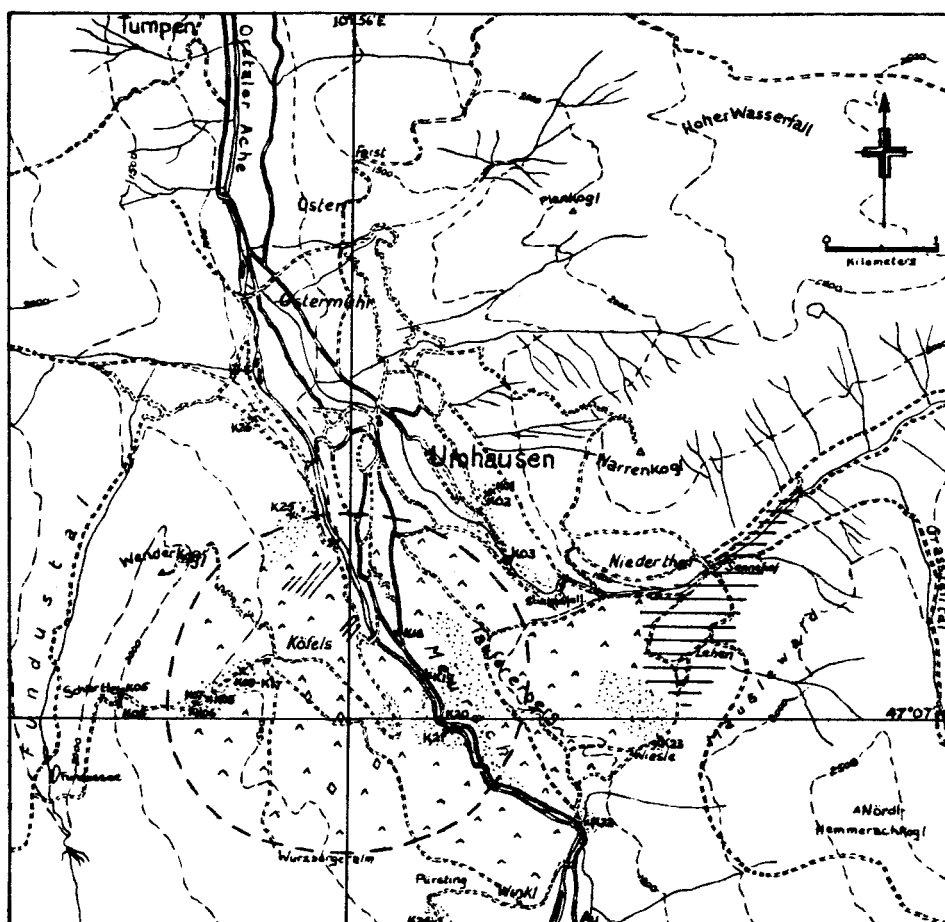
- Lineaments (trace of fracture & joint planes)
- - - Inferred geological contacts (gneissic banding & foliation)
- a — b (a) Esker (b) glacial striae
- x Outcrop at which geological observations were made
- a — b Strike & dip of gneissosity (a) inclined (b) vertical
- a — b Strike & dip of major joints planar (a) inclined (b) vertical
- a — b Strike & dip of sheeting joints (a) inclined (b) vertical
- a — b Strike & dip of shear zones
- a — b Plunge of (a) 'b' lineation (b) drag folds
- a — b Axis of folds (a) antiform (b) synform

○ Lake

#### ROCK TYPES

- Diabase
- Mainly massive coarse-grained granite gneiss, quartz-feldspar-biotite gneiss, with lesser amounts of quartz-feldspar-epidote gneiss, quartz-feldspar-mica schist, and enclaves and schlieren of amphibolite.





Map Showing the Location of Specimens and Some Geology of the Köfels Crater, Ötztal, Austria.

**LEGEND**

- Granite-gneiss
- Paragneiss
- Scree-throut material
- Suiveite
- Lake sediments
- Elevations in meters

**SOURCE**

Geology after F. Süss, 1936 & V. Vand, 1964  
Specimens collected by V. Vand, 1964. Data compiled by D.P. Gold, 1964.